SIMPLE HIGH EFFICIENCY OPTICAL COHERENCE DOMAIN REFLECTOMETER DESIGN

Inventors: Matthew J. Everett and Yan Zhou

BACKGROUND OF THE INVENTION

1. Field of the invention:

The invention relates generally to optical imaging and in particular to systems and methods for achieving flexibility in interference fringe visibility control and optimization of signal to noise ratio, as well as for achieving polarization insensitivity, dispersion matching and optical output polarization control in optical coherence domain reflectometry (OCDR) or optical coherence tomography (OCT).

2. Description of Related Art

Optical coherence domain reflectometry (OCDR) is a technique initially developed to provide a higher resolution over optical time domain reflectometry (OTDR) for the characterization of the position and the magnitude of reflection sites in such optical assemblies as optical fiber based systems, miniature optical components and integrated optics (Youngquist et al., "Optical Coherence-Domain Reflectometry: A New Optical Evaluation Technique", 1987, Optics Letters 12(3):158-160). With the addition of transverse scanning, this technique has been widely and successfully extended to the imaging of biological tissues, and is termed optical coherence tomography (OCT) (Huang, D., E. A. Swanson, et al. (1991). "Optical coherence tomography." <u>Science</u> **254** 1178-81; and U.S. Patent Nos. 5321501 and 5459570). Since then, a large number of applications have been found for this technology as evidenced by a number of review articles (Swanson E. A. et al. "Optical coherence tomography, Principles, instrumentation, and biological applications" Biomedical Optical Instrumentation and Laser-Assisted Biotechnology, A. M. Verga Scheggi et al. (eds.) pages: 291-303, 1996 Kluwer Academic Publishers, Printed in the Netherlands; Schmitt, J.M. "Optical coherence tomography (OCT): a review" IEEE Journal of Selected Topics in

Quantum Electronics, Volume: 5, Issue: 4, Year: Jul/Aug 1999, pages: 1205-1215; Fujimoto, J.G. et al. "Optical Coherence Tomography: An Emerging Technology for Biomedical Imaging and Optical Biopsy" *Neoplasia* (2000) **2,** 9-25; Rollins A. M. et al. "Emerging Clinical Applications of Optical Coherence Tomography" Optics and Photonics News, Volume 13, Issue 4, 36-41, April 2002; Fujimoto, J. G. "Optical coherence tomography for ultrahigh resolution in vivo imaging." Nat Biotechnol **21**(11): 1361-7, (2003)). Each of these documents is incorporated herein by reference.

The most straightforward and most commonly used interferometer configuration for OCDR or OCT is a standard Michelson interferometer. As shown in Fig. 1, light from a low coherence source **110** is input into a beam splitter or 2×2 fiber optic coupler **112**, where the light is split and directed into a sample arm **114** and a reference arm **116**. An optical fiber **118** in the sample arm **114** extends into a device **120** that scans an object **122**. The reference arm **116** provides a variable optical delay. Light input into the reference arm **116** is reflected back by a reference mirror **124**. A piezoelectric modulator **126** may be included in the reference arm **116** with a fixed reference mirror **124**, or the modulator **126** may be eliminated by scanning the mirror **124** in the Z-direction. The reflected reference beam from reference arm **116** and the scattered sample beam from sample arm **114** pass back through the coupler **112** to detector **128** (including processing electronics), which processes the signals by techniques that are known in the art to produce a backscatter profile or image on a display unit **130**.

This configuration is advantageous in that it uses a minimum number of optical components and is hence the simplest. It can be implemented using bulk or fiber optics or a combination thereof. However, this configuration is limited to an optical efficiency of 25% as explained below.

By examining the configuration, it is not difficult to discover that the optical power reaching the detector from the two arms is reciprocal with respect to the beam splitter or fiber coupler (BS/FC). Assuming that the power split ratio of the beam splitter is $\frac{\alpha}{1-\alpha}$ and neglecting loss in the splitter, the attenuation by the beam splitter or the fiber coupler (BS/FC) to both the sample optical wave and the reference optical wave is the same and is equal to $\alpha(1-\alpha)$, the only difference is that for one wave it will propagate straight-

through the BS/FC first with an attenuation by a factor of α and then crossover the BS/FC with a further attenuation by a factor of $(1-\alpha)$, whereas for the other wave, it will crossover the BS/FC first with an attenuation by a factor of $(1-\alpha)$ and then propagate straight-through the BS/FC with a further attenuation by a factor of α. It is well known to those skilled in the art that for such a configuration, the most efficient power splitting ratio is 50/50, where $\frac{\alpha}{1-\alpha}=1$, simply because the function $\alpha(1-\alpha)$ has its maximum value when $\alpha=0.5$. For example, with a 50/50 power split ratio, for either the sample arm or the reference arm, the optical power is firstly attenuated at the BS/FC by 50% from the light source to the sample or reference arm and then further attenuated by 50% from the sample or reference arm to the detector, which leads to a total overall power attenuation factor of 50%×50% = 25% for both arms. If the BS/FC power split ratio is 90/10, then for the reference and the sample arm respectively, the total overall power attenuation factor by the BS/FC will be 90%×10% and 10%×90%, which is the same and is equal to only 9%.

Various configurations have been proposed to improve the optical power efficiency. The configuration described in this patent is simpler than those previously proposed designs and also addresses polarization fading issues that are not addressed by the other high optical efficiency designs.

Rollins and Izatt (U.S. Patent No. 6,657,727; Andrew M. Rollins, Joseph A. Izatt "Optimal interferometer designs for optical coherence tomography" Optics Letters, Vol. 24, Issue 21, Page 1484 (1999)) proposed a number of interferometer configurations to improve the optical efficiency of the above Michelson interferometer configuration. As shown in Fig. 2, a key optical element that is used in all their configurations is a commercially available non-reciprocal device called an optical circulator and such a circulator is combined with unbalanced couplers, and (or) balanced heterodyne detection for optical power efficient interferometer construction. In contrast, the design we describe herein eliminates the optical circulator, a complex and expensive component. Our design is also very compact and relatively low cost as it uses a minimum number of optical elements.

It should be pointed out that Fig. 2 encompasses six configurations where the three insets (Figs. 2Aii; 2Bii and 2Cii) basically show a modification from the three

corresponding balanced heterodyne detection approach employing balanced couplers to a single detector based detection employing unbalanced coupler(s) as shown in the main Figures 2Ai; 2Bi and 2Ci . Refer now to the first two configurations (Figs. 2Ai and 2Aii), which are based on a Mach-Zehnder interferometer with the sample **222** located in a sample arm **214** and the reference optical delay line (ODL) **225** in the reference arm **216**. In the case of 2Ai, the main difference from a standard Mach-Zehnder interferometer is that the prior fiber coupler **212** has an optical power split ratio of $\frac{\alpha_1}{1-\alpha_1}$ instead of 50/50 that is optimized for optical power efficient high SNR detection by directing most of the original optical power to the sample arm **214** and meanwhile light is coupled to the sample **222** through an optical circulator **232** such that the backscattered optical signal is collected by the delivery fiber **218** but is redirected to the post fiber coupler **234**. The reference arm ODL **225** may be transmissive using, for example, a fiber wrapped PZT based fiber stretcher or it may be retroreflective using, for example, a corner mirror or cube combined with another optical circulator (not shown, see U.S. Patent No. 6,657,727). Note that in Fig. 2Ai, the post fiber coupler **234** has a split ratio of 50/50 and due to the employment of balanced heterodyne detection **236**, Izatt and Rollin showed that the SNR of Fig. 2Ai can be improved over that of a standard Michelson configuration as shown in Fig. 1.

In the configuration of Fig. 2Aii, the post fiber coupler **238** is also made non-50/50 and a single detector **240** is used. The advantage of Fig. 2Aii embodiment as compared to Fig. 2Ai embodiment is that since only one detector is used, the cost of the system will be lower than that of Fig. 2Ai.

Refer now to Figs. 2Bi and 2Bii, while the sample arm part is the same as in Figs. 2Ai and 2Aii, the reference arm ODL **242** is made retroreflective but without the need of a second optical circulator. Again, the optical power split ratio of both the prior fiber coupler **244** and the post fiber coupler **246**, $\frac{\alpha_1}{1-\alpha_1}$ and $\frac{\alpha_2}{1-\alpha_2}$, can be properly chosen for either the two detector based balanced heterodyne detection case **248** or the unbalanced single detector case **250** to optimize the SNR such that the system is optical power efficient. Izatt and Rollin showed that the SNR improvement of the Figs. 2Bi and 2Bii embodiment is very similar to that of Figs. 2Ai and 2Aii embodiments. Note that there will be a small

portion of the optical power from the reference ODL **242** being returned to the light source path.

The configurations of Figs. 2Ci and 2Cii are basically Michelson interferometer based and their difference as compared to Fig. 1 is the use of an optical circulator **252** in between the light source **254** and the fiber coupler **256** to channel the returned light from the fiber coupler **256** initially propagating towards the light source **254** now completely to the detector, **d2**. While for balanced heterodyne detection, the optical power split ratio of the fiber coupler **256** must be made 50/50, it should be noted that for the case of a single detector unbalanced detection **258** (Fig. 2Cii), the optical power delivered to detector **d2** from the sample arm **260** and the reference arm **262** can be made different or non-reciprocal since for detector **d2**, the sample optical signal will propagate straight-through the fiber coupler **256** twice and the reference optical signal will cross-over the fiber coupler **256** twice. As a result, the optical power delivery to detector **d2** can be made efficient by properly selecting the fiber coupler optical power split ratio $\frac{\alpha}{1-\alpha}$. Izatt and Rollin stated that for the configuration shown in Figs. 2Ci, the SNR can be improved over that of Fig.1 and although this configuration is not as power efficient as the other two, i.e. Figs. 2Ai and 2Bi, its significant advantage is that it can be easily retrofitted with a circulator in the source arm and with a balanced receiver, with no need to disturb the rest of the system. As for Fig. 2Cii, the SNR improvement is similar to that of Figs. 2Aii and 2Bii.

As an extension to all their configurations, Izatt and Rollin included, in their patent (U.S. Patent No. 6,657,727), three more configurations as shown in Fig.3 in which a transmissive sample is in the place of the circulator and the sample. They defined a transmissive sample as any sample illumination and collection geometry in which the illumination and collection optics occupy separate optical paths. Such designs have significant alignment issues and are not relevant to the invention being described where the illumination and collection optics occupy the same optical path.

As can be seen from the above-mentioned various configurations, the key advantage of these prior configurations lies in the improvement of the optical power delivery

efficiency to the detector(s), by properly selecting an optical power split ratio $\frac{\alpha}{1-\alpha}$ (for either the prior and/or the post fiber coupler).

Another issue with the classic Michelson interferometer (Fig 1) is that light from the reference arm is coupled back into the optical source, causing side effects that can impact the quality of the resulting image. Most of the configurations proposed by Izatt and Rollins address this issue as does the invention described herein. An issue not addressed by Izatt and Rollins configurations above is polarization fading, or loss of signal associated with mismatches between the polarization states of the light from the reference and sample arms. These mismatches are caused by birefringence and its fluctuations in the sample and reference arms, generally dominated by the birefringence in the optical fibers.

For a retraced light wave, placement of Faraday rotators at the ends of the fibers has been shown in the prior art to eliminate polarization fading due to the fiber optic components. Fig.4 shows the approach of using two Faraday rotator mirrors at the end of the two arms of a standard Michelson fiber optic interferometer to eliminate polarization fading (Kersey, A.D. et al. "Polarization-insensitive fiber optic Michelson interferometer", Electronics Letters, Volume: 27, Issue: 6, pages: 518-520, (1991)). In this design, the Faraday rotator and mirror enable birefringence compensation in a retraced fiber path for both the sample arm and the reference arm. Although this design solved the problem of polarization fading, it did not address the issue of optical efficiency as the optical splitter configuration is the same as the standard Michelson interferometer configuration of Fig 1. The invention described herein takes advantage of the polarization rotation caused by the Faraday rotators to increase the optical efficiency of the system by introducing a polarizing beam splitter in the source arm for coupling the light returning toward the source into a detector. This leads to an unbalanced optical efficiency assuming no birefringence in the sample and the use of a polarized source. An additional advantage of such a system is that the light being collected on the detector is linearly polarized, which is advantageous for spectral domain optical coherence tomography and reflectometry systems.

In spectral domain OCT systems, the light is dispersed by a diffraction grating and collected by an array of detectors. The efficiency of the diffraction grating is generally

polarization dependent, and thus can be made most efficient for linearly polarized light. As will be elaborated later, the present invention can meet such a requirement.

In order to partially address the polarization fading problem, U.S. Patent No. 6,564,089 by Izatt et al. mentioned the provision of a polarization compensation means such as a Faraday rotator on the side of the light emission of the optical probe on top of some of the interferometer configurations as discussed before with respect to Fig.2. By doing so, the OCT can obtain a stabilized interference output regardless of the state of the bend of the sample arm. The inclusion of a Faraday rotator at the end of the sample arm optical probe only is particularly related to the application of OCT to endoscopic biological imaging in which the sample arm optical probe beam needs to be rotated to acquire cross sectional images of a tubular tissue and hence the birefringence property of the sample arm is very vulnerable to fluctuations. A drawback of such a system is the additional cost of the Faraday rotator and furthermore, while polarization compensation is provided for the sample arm, the same is not provided for the reference arm and as a result, there will be a mismatch in the birefringence as well as the dispersion properties between the two arms. Obviously, any birefringence fluctuation in the reference arm will still cause polarization fading and at the same time, the final output optical polarization of the configuration is not predetermined and hence is not suitable for spectral domain OCT which is polarization dependent.

In terms of addressing the polarization fading issue, besides using Faraday rotators, an alternative approach is to use polarization-maintaining (PM) fibers. In addition, a so-called polarization diversity receiver (PDR) scheme (Sorin, et al. "Polarization independent optical coherence-domain reflectometry" U.S. Patent No. 5,202,745) can also be used. There are also combinations in which PM-fiber, polarization control optical elements and FRM are used (Everett M. et al. "Birefringence insensitive optical coherence domain reflectometry system" U.S. Patent No. 6,385,358). PM fibers have several issues associated with their two orthogonal polarization axes, which make them undesirable for commercial OCDR or OCT applications. These include variable optical dispersion, difficulties in maintaining high polarization extinction in the connection between two PM-fibers or between a PM-fiber and a polarization optical component, and high cost.

Fig. 5 shows Sorin, et al.'s polarization independent optical coherence-domain reflectometry configuration (U.S. Patent No. 5,202,745), where the light returning from the

sample and reference arms is split into two orthogonal polarization modes with each mode being detected by a separate detector. In this design, a linear polarizer in the reference arm is adjusted to compensate for birefringence in the reference arm so as to equal signal powers on each detector in the detector arm in the absence of a signal from the test, or sample, arm. The problem with this approach is that the polarizer needs to be adjusted as the birefringence in the reference arm changes. As the birefringence in the non-PM reference arm fiber is strongly affected by temperature and stress, the system must be recalibrated with each use, and suffers from polarization drift during use.

An alternate design for a fiber optic polarization insensitive OCDR system with non-PM fiber in the sample arm has previously been described (Kobayashi et al, "Polarization-Independent Interferometric Optical-Time-Domain Reflectometer", 1991, J. Lightwave Tech. 9(5):623-628). The reference arm in this system consists of all PM optical fiber. As the two arms use different types of optical fibers, their dispersion properties are drastically different, which hence will lead to loss of resolution due to mismatched dispersion between the sample and reference arms. The system also requires a specialized 50/50 coupler.

U.S. Patent No. 6,385,358 disclosed a hybrid system involving the use of PM fibers, non-PM fibers and Faraday rotators. An important feature in this patent is the use of a 22.5° Faraday rotator in the beam path to enable a double path rotation of the polarized beam returned from reference arm so that the beam is equally split into two orthogonal polarization modes to interfere with the two corresponding but not necessarily equally split components of the beam from the sample arm, which are then detected by two detectors. By summing the interference signal envelops from the two detectors, the final signal is made independent of the birefringence of the sample arm in a similar way as in the case of a polarization diversity receiver. In addition to polarization insensitivity, the dispersion property of the sample arm is also matched with that of the reference arm to eliminate the dispersion effects that degrade image resolution. Furthermore, arbitrary power split ration $\alpha/(1-\alpha)$ fiber coupler is also used to enable high efficiency optical power delivery to the detector. Considering that for medical applications, the portion of the fiber optic interacting with the patient must be changed for hygienic reasons, a non-PM fiber is incorporated into the sample arm to accommodate a disposable section at the end of the sample arm that

interacts with the sample. However, a major disadvantage of the disclosed designs is that the system configuration is not simple at all, as it involves length matched PM fiber and non-PM fiber between the sample and references arms, their splices or connections and the use of a relatively large number of various optical components such as (PM or non-PM) fiber coupler, free space polarization beam splitter (PBS), various Faraday rotators of different rotation angles, and two photodetectors. In the case of a 22.5° Faraday rotator which is placed between a single PM fiber and a single mode non-PM fiber, the light beam needs to be expanded from a first fiber, collimated, passed through the Faraday rotator, and then refocused into the other fiber. All of these make the system both quite complicated and also expensive.

Given the problems with the systems described above, there is obviously a need to combine the benefit of optical power delivery efficiency with polarization insensitivity as well as dispersion matching in a simply configuration that will lower the cost and enhance the performance. The present invention addresses the above-mentioned problems and significantly improves on the prior art systems by effectively achieving high optical power delivery efficiency, polarization insensitivity and also dispersion matching, in a more compact, more robust, and also less expensive manner.

SUMMARY OF THE INVENTION

The present invention discloses simple configurations of optical coherence domain reflectometry systems that are polarization insensitive and also highly efficient in terms of optical power delivery to the detector(s). In particular, a unique feature of the present invention is the combined use of a polarizing beam splitter with one or two polarization manipulator(s) that rotate the returned light wave polarization to an orthogonal direction. Such a combination provides the flexibility in interference fringe visibility control and the optimization of signal to noise ratio, as well as the possibility of polarization insensitivity, dispersion matching and optical output polarization control in an optical coherence domain reflectometry (OCDR) or optical coherence tomography (OCT) system.

In one aspect of the invention, an OCDR system (embodiment 1) includes a light source; a polarizing beam splitter having at least three ports; a non-polarizing beam splitter having at least three ports that is optically connected with the polarizing beam

splitter; a sample arm leading to a sample that is optically connected to a first output port of the non-polarizing beam splitter; a reference arm leading to a reflector that is optically connected to a second output port of the non-polarizing beam splitter; one or two polarization manipulator(s) that rotate the returned polarization to an orthogonal direction, a detector that collects light combined by the non-polarizing beam splitter from the sample and reference arms, returned to the polarizing beam splitter in an orthogonal polarization state, and thus channeled by the polarizing beam splitter to the detector path for interference signal detection and processing.

Another aspect of the present invention is to provide a method for performing optical coherence domain reflectometry comprising the steps of: guiding a light beam through a polarizing beam splitter and a non-polarizing beam splitter into a sample arm leading to a sample, and a reference arm leading to a reflector; rotating the polarization direction of returned light waves from said sample and said reflector to an orthogonal direction, followed by combining said returned light waves in said non-polarizing beam splitter, or combining returned light waves from said sample and said reference reflector in said non-polarizing beam splitter, and rotating the polarization direction of said returned light waves to an orthogonal direction; guiding said returned light waves to said polarizing beam splitter; and channeling at said polarizing beam splitter said combined and returned light waves having an orthogonal polarization state to a detector for interference signal extraction and processing.

In another aspect of the present invention, an OCDR system (embodiment 2) is disclosed that includes a light source; a polarizing beam splitter having four ports, for receiving the light from said source through a first port, splitting the light into a second port and a third port, combining the light returned from the second port and third port, and channeling the combined light to a fourth port; a sample arm containing a polarization manipulator that rotates the returned light wave polarization to an orthogonal direction and a sample, wherein the sample arm is optically connected to the second port of the polarizing beam splitter; a reference arm containing a polarization manipulator that rotates the returned light wave polarization to an orthogonal direction and a reflector, wherein the reference arm is optically connected to the third port of the polarizing beam splitter; an analyzer for combining into a common polarization direction, two orthogonally polarized light waves,

each from the sample and reference arms respectively, propagation-directionally combined and channeled by the polarizing beam splitter; and a detector (or two detectors) for collecting the polarization-direction-combined light for interference signal extraction.

Still another aspect of the present invention is to provide a method for performing optical coherence domain reflectometry comprising the steps of: guiding a light beam through a polarizing beam splitter into a sample arm containing a polarization manipulator that rotates the returned light wave polarization to an orthogonal direction and a sample, and a reference arm containing a polarization manipulator that rotates the returned light wave polarization to an orthogonal direction and a reflector; combining in the polarizing beam splitter, the returned light waves from the sample arm and the reference arm; channeling at the polarizing beam splitter, the combined and returned light waves having mutually orthogonal polarization states through the forth port to an analyzer and detector arm; projecting at the analyzer the two mutually orthogonally polarized light waves from the sample and reference arms respectively onto one (or two) polarization-passing-through-axis(es) of the analyzer; and collecting at the detector(s), the polarization-direction-combined interfering light wave(s) for interference signal extraction and processing.

An object of the invention is to achieve high optical power delivery efficiency, polarization insensitivity as well as dispersion matching at the same time in a simple reflective-arms-based optical interferometer configuration, and this is realized through a combined use of a polarizing beam splitter with one or two polarization manipulator(s) that rotates the returned light wave polarization to an orthogonal direction.

A second object of the invention is to achieve a predetermined or fixed polarization direction of the final combined interfering light waves at the detector or detection module so that a polarization sensitive detector or detection module can be used for such cases as spectral domain optical coherence tomography (SD-OCT).

A further object of the invention is to use non-PM fiber and non-PM fiber pigtailed fiber optic devices so that the cost of the system is much lower than PM fiber based counterparts.

Another object of the present invention is to make it possible to adjust the polarization direction of the light wave projecting onto the sample without causing polarization fading resulting from the birefringence changes in the sample arm.

Another object of the present invention is to make it possible to achieve optical path length delay or phase modulation using a fiber-wrapped PZT based transmissive optical delay line in the lead non-PM fiber portion of either the reference arm or the sample arm, without causing polarization fading resulting from the birefringence changes in the fiber portion of the reference or sample arm.

Another object of the present invention is to also provide a configuration (embodiment 2) that can be easily converted between a two-detector-based balanced heterodyne detection scheme and a one detector based unbalanced detection scheme.

Still another object of the invention is to further lower the cost of an OCDR system by using a thin film base analyzer to achieve the one detector based unbalanced detection scheme in embodiment 2.

These and other features and advantages of the present invention will become more readily apparent to those skilled in the art upon review of the following detailed description of the preferred embodiments taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a standard Michelson interferometer configuration used for OCDR or OCT.

Fig. 2 shows 6 different interferometer configurations in which the optical power delivery efficiency to the detector(s) is improved as compared to the standard Michelson interferometer configuration.

Fig. 3 shows some extensions of Fig.2 in which the sample arm is transmissive in the sense that the illumination and collection optics geometry occupy separate optical paths

Fig. 4 shows a prior art polarization insensitive Michelson interferometer configuration in which two 45° Faraday rotators are used at the end of the sample and reference arms.

Fig. 5 shows another prior art polarization insensitive configuration called polarization diversity detection scheme.

Fig.6A shows a fiber optics version of a first embodiment of the presently invented interferometer configuration which is highly optical power efficient as well as polarization insensitive.

Fig.6B shows a bulk optics version of a first embodiment of the presently invented interferometer configuration which is highly optical power efficient as well as polarization insensitive.

Fig. 6C shows a bulk optics version of a first embodiment of the presently invented interferometer configuration which uses only one polarization manipulator and is highly optical power efficient as well as polarization insensitive.

Fig. 7A shows a fiber optics version of a second embodiment of the presently invented interferometer configuration which is highly optical power efficient as well as polarization insensitive.

Fig. 7B shows a bulk optics version of a second embodiment of the presently invented interferometer configuration which is highly optical power efficient as well as polarization insensitive.

Fig. 8 shows an exemplary detection module particularly useful for spectral domain OCT, which is often polarization sensitive hence preferring a predetermined polarization state of the interfered optical waves.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is an optical coherence domain reflectometer (OCDR) system with a high optical power delivery efficiency and also fiber birefringence insensitivity that can use non-polarization maintaining (non-PM) fibers. Here, the term optical coherence domain reflectometer (OCDR) is used to refer to a system that employs a light source in an optical interferometer to achieve high resolution with a large dynamic range in terms of resolving the light signals reflected or scattered from a sample. Hence the term OCDR covers various modification of the basic technology, which, in addition to the traditional or conventional OCDR/OCT, also includes frequency-domain or Fourier-domain or spectral-domain optical coherence tomography.

An important feature in the presently disclosed configuration of the invention is a combined use of a polarization beam splitter with one or two polarization manipulator(s)

that rotate the returned light wave polarization to an orthogonal direction. Such a combination brings a number of advantages to an OCT system, including optimized interference fringe visibility and hence enhanced SNR with shot noise limited interference detection, fixed or predetermined polarization state of the output interfering light waves, insensitivity to fiber birefringence fluctuations, dispersion matching and others as will be made clear below.

EMBODIMENT 1

Fig. 6A is a diagram of the OCDR system according to a first embodiment of the present invention. The light source **610a** introduces to the system **600a** a linearly polarized light wave either through a linearly polarized light source **610a** or by placing a linear polarizer (not shown) directly after an unpolarized source, wherein the linear polarizer can be an independent polarizer or the polarizing beam splitter as will be made clear below. The light source **610a** has a center wavelength within the optical spectrum range from ultra-violet to near infrared. It is preferably derived from a superluminescent diode (SLD), a light emitting diode (LED), a short pulsed laser such as a Ti:sapphire laser, a photonic crystal fiber laser or a spontaneous emission based rare earth doped optical fiber broad band light source. For these applications, the latter light sources are considered "low coherence" light sources. The subject invention can also be implemented with a frequency swept laser. The light source **610a** is coupled through a short length of a non-PM fiber **612a** to the input port (port I) of a polarizing/polarization beam splitter (PBS) **614a**. It is well known to those skilled in the art that the PBS **614a** may be based on a polarization beam splitter cube, in which case the light wave from a fiber needs to be collimated using, for example, a graded refractive index (GRIN) lens, and refocused into another fiber using, for example, another GRIN lens, if this is desired. The PBS may also be purely fiber optics based in which case polarization-maintaining (PM) fibers may be present. It should also be noted that as the light source **610a** can be polarized or unpolarized, if it is polarized, a polarization-maintaining (PM) fiber may have already been pig-tailed for the light source and such a PM fiber can be used to connect the light source **610a** to the PBS **614a** to maintain the polarization state. It should be pointed out that non-PM fiber or PM fiber pig-tailed polarization beam splitters are commercially available and their price is much less than that of a fiber pig-tailed optical circulator.

Preferably, the polarized light wave from the light source arm is already in the correct polarization state or direction so that except for the insertion loss introduced by the polarizing beam splitter **614a**, the input light power is substantially coupled to the output port (port II). If the input polarization state is not in the desired state or direction, a non-PM single mode fiber based polarization controller **611a** can be placed in front of the PBS **614a** to adjust the input polarization state to the desired direction. Although a non-PM fiber based polarization controller **611a** is preferred here, other types of polarization controller can also be used, for example, a bulk optical wave plate based polarization controller is also a choice. Meanwhile, in spite of the fact that a non-PM fiber pig-tailed polarizing beam splitter is preferred here, this statement does not exclude the use of PM fiber pig-tailed PBS, although the latter may be more expensive than the former due to the additional requirement of rotational alignment of the PM fibers.

The polarized output from port II of the polarizing beam splitter **614a** is sent through a short length of non-PM fiber **616a** to a non-polarizing beam splitter or a non-PM fiber based coupler **618a** having a desired optical power split ratio $\frac{\alpha}{1-\alpha}$ (say, for example, $\frac{\alpha}{1-\alpha}=\frac{90}{10}$) so that most of the light (for example α= at least 70% and preferably 90%) is coupled to the sample arm **620a** and a small portion of the input light (for example $(1-\alpha)=10\%$) is coupled to the reference arm **622a**.

The sample arm contains a certain length of a non-PM single mode fiber **624a**, an optical probe module **630a** and a sample **632a**. The non-PM single mode fiber **624a** can have any reasonable length as long as it approximately matches the length and dispersion property of the non-PM single mode fiber **640a** in the reference arm **622a**. It should be noted that here dispersion matching is desirable but not absolutely required. A preferred practice is to cut a single piece of a non-PM fiber into two pieces of substantially the same length with one for the sample arm and the other for the reference arm so that their dispersion property is also well matched.

The optical probe module **630a** includes some light beam shaping and focusing elements, light beam bending or steering or scanning elements (not shown) such as pivoted scanning or dithering mirrors, and a polarization manipulator **634a**, wherein the

polarization manipulator can be a Faraday rotator or a wave plate. It should be noted that in the optical probe module **630a**, the arrangement of various optical elements can be of any order or sequence. Although it is preferred that the polarization manipulator **634a** is placed at the end of the sample arm just in front of the sample, in practice, it may be more reasonable to place the polarization manipulator **634a** before any translational or mechanically movable components, and perhaps the easiest place to put it is at the end or tip of the fiber **624a,** as such a Faraday rotator tipped fiber piece is commercially available.

Light reflected from various optical interfaces or scattered from within the sample **632a** is collected by the same optical probe module **630a** and is directed back through the same non-PM optical fiber **624a** in the sample arm **620a** to the non-polarizing beam splitter or the non-PM fiber coupler **618a**. Note that if the polarization manipulator is a 45° Faraday rotator **634a** as discussed previously with respect to Fig. 4 and the sample, when reflecting or scattering the light wave, does not alter the light wave polarization direction, the polarization state or direction of the returned light wave will be rotated by 90° after double-passing the non-reciprocal Faraday rotator **634a** to an orthogonal direction with respect to the polarization direction of the original forward-propagating light beam before it hits the Faraday rotator **634a**. Thus, except for the biological sample or components in the sample arm after the Faraday rotator **634a**, any birefringence-induced polarization sensitivity or fading effect introduced to the sample arm light wave in the forward direction will be completely compensated for or cancelled when the light wave propagates in the backward direction. It should be highlighted that because of this feature, if a polarization controller is included in the fiber section **624a** of the sample arm **620a**, a desired final polarization state of the light beam shining onto the sample can be selected to take full advantage of a biological sample if its light reflection or scattering property is polarization dependent and this polarization controlling will obviously not influence the final well-aligned interfering beam polarization directions from the sample arm and the reference arm (as will be discussed shortly) because of the polarization-insensitive fiber optic Michelson interferometer configuration. For example, one can maximize the final optical interference signal if for certain optical boundaries or interfaces the amount of reflected light is more intense in one polarization direction than the other or to examine the birefringence properties of the biological sample.

On the other hand, if the sample is a biological sample that has a relatively large birefringence that can not be ignored and is more or less predictable, the polarization manipulator may be selected in such a way that when it is combined with the birefringence of the biological sample, a substantially 90° polarization direction rotation for the returned light wave with respect to the original forward propagating light wave is realized. Such a polarization manipulator can be either a wave plate or a combination of a polarization controller and a wave plate, wherein the polarization controller can select a desired polarization direction with respect to the wave plate and the biological sample, and the wave plate can combine its birefringence with that of the biological sample to provide a net quarter wave plate effect.

When the returned light wave from the sample arm **620a** passes though the non-polarizing beam splitter or the non-PM fiber coupler **618a** back to the non-PM fiber **616a**, the optical power will be further attenuated by a factor of α (for example, α=90%) as has been discussed previously with respect to Fig. 2Cii. As a result, the overall attenuation to the sample light wave introduced solely by the non-polarizing beam splitter or the non-PM fiber coupler **618a** for a round trip will lead to an optical power efficiency of α^2 (for example: α^2 = 90%×90%=81%). It is assumed here that the optical power split ratio of the non-polarizing beam splitter or the non-PM fiber based coupler **618a** is polarization-independent, which is generally the case. However, the statement should not exclude the case of a non-PM fiber based coupler that may be slightly polarization sensitive due to imperfection in the fabrication of the coupler and in which case, the attenuation for the returned light wave may be slightly different from that for the forwarding propagating light wave.

Note that as the polarization direction is now rotated by 90° for the returned light wave from the sample arm **620a** to the polarizing beam splitter **614a**, except for the insertion loss, basically all of the returned light wave will now be channeled to port III of the polarizing beam splitter **614a** (as is well known to those skilled in the art), and if both the non-polarizing beam splitter or the non-PM fiber coupler **618a** and the polarizing beam splitter **614a** are perfect, there will be no light returning to the light source arm. This is

obviously an advantage as has already been discussed with reference to Fig.2 because any returned light to the light source might disturb the light emitting property.

Furthermore, if a short length of non-PM fiber **650a** is used to guide the light wave to a detector (or a light detection module) **652a** such that the polarization state is not altered by the short length of the non-PM fiber **650a**, the polarization state (or direction) of the light wave reaching the detector (or light detection module) **652a** will be fixed and predetermined. While for a polarization independent photodetector, this fixed and predetermined polarization state of the arriving light wave is not critical, it is actually very critical for the spectral-domain optical coherence tomography (SD-OCT) detection scheme since in such a system, the grating used to disperse the constituent wavelength components of the broadband optical signal is generally sensitive to the polarization direction of the input beam and hence a fixed or predetermined polarization direction of the input beam to the grating will be extremely beneficial.

In the reference arm, there should preferably be a non-PM single mode fiber **640a** that is approximately matched in length and dispersion property with the non-PM single mode fiber **624a** in the sample arm. It is preferred that the optical delay line **642a** is incorporated in the reference arm **622a** and this reference delay line **642a** may be a transmissive one to be implemented in the fiber section **622a** which can be achieved by wrapping a certain length of optical fiber around a piezoelectric cylinder. In fact, for a standard polarization sensitive OCT configuration such as those shown in Fig.1 and Fig.2, such an optical fiber wrapped PZT based optical delay line will generally introduce a substantial amount of polarization fading as a result of the birefringence change during the optical path length scanning or optical phase modulation process, but with the presently invented configuration, this is no longer an issue any more because of the polarization insensitivity nature and hence it might be advantageous to use such a fiber wrapped PZT based optical path length delay line. Although implementing the optical delay line in the reference arm **622a** is preferred here, it should be noted that the optical delay line can also be located in the sample arm or both arms may have an optical delay line with the two operating in a push-and-pull mode or in any other manners as desired such as with one modulating the path length to achieve a depth scan and the other modulating the optical phase to obtain a high carrier frequency for the interference signal. Alternatively, an independent optical delay

line may be used after the fiber **640a** and a good example is a grating based phase control optical delay line as disclosed in U.S. Patent Nos. 6,111,645 and 6,282,011. Other retro-reflective optical delay lines such as those employing corner mirror(s) or corner prism cube(s) may also be used. The overall optical path length for the reference arm **622a** should roughly match that of the sample arm **620a** and this can be achieved by letting the reference light wave traveling through some free space and/or some other optical elements. By roughly matching the overall optical path length between the reference arm **622a** and the sample arm **620a**, the requirement for the scan range of the optical delay line **642a** can be lowered and data acquisition time for one depth scan can thus be reduced to a minimum. The reference arm **622a** may also contain some light collimating and/or focusing optical elements **644a**, and there should be a polarization manipulator such as a 45° Faraday rotator **646a** and a mirror **648a** to reflect the reference light wave back to the non-polarizing beam splitter or the non-PM fiber coupler **618a**. The position of the 45° Faraday rotator **646a** is preferably at the end of the reference arm **622a** and right in front of the mirror **648a** so that polarization fading caused by any birefringence or birefringence fluctuations introduced by all the optical elements prior to the Faraday rotator **646a** in the reference arm **622a** can be completely compensated for and hence cancelled. However, it should be noted that the 45°Faraday rotator **646a** can be placed anywhere between the end of the non-PM fiber **640a** and the mirror **648a**. It is perhaps more economic to directly use a mirrored 45°Faraday rotator as such a device is now commercially available, and in such a case, the reference arm fiber **640a** may be selected to be longer than the sample arm fiber **624a** such that the overall optical path length between the sample arm **624a** and the reference arm **622a** is roughly matched.

Similar to what has been discussed for the sample arm **620a**, the light wave returned from the mirror **648a** is collected by the same optical element(s) **644a** & **646a** and is directed back through the same non-PM optical fiber **640a** in the reference arm **622a** to the non-polarizing beam splitter or the non-PM fiber coupler **618a**. Due to the use of the 45° Faraday rotator **646a**, the polarization state or direction of the returned light wave will be rotated by 90° after double-passing the non-reciprocal Faraday rotator **646a** to an orthogonal direction with respect to the polarization direction of the original forward-propagating light

wave in the reference arm **622a** before it hits the Faraday rotator. As a result, any birefringence-induced polarization sensitivity or fading effect introduced to the reference arm light wave in the forward direction will be completely compensated for or cancelled when the light wave propagates in the backward direction.

When the returned light wave from the reference arm **622a** passes through the non-polarizing beam splitter or the non-PM fiber coupler **618a** back to the non-PM fiber **616a**, the optical power of the reference wave will be further attenuated by a factor of 1-α (for example, 1-α=10%). Note that the overall attenuation to the reference light wave introduced solely by the non-PM fiber coupler **618a** for a round trip will have an optical power efficiency of $(1-\alpha)^2$ (for example: $(1-\alpha)^2 = 10\%\times10\%=1\%$), which is different from that to the sample arm (α^2, for example: $\alpha^2 = 90\%\times90\% = 81\%$). For OCT based bio-sample imaging, a low optical power efficiency for the reference arm **622a** is desirable as long as the photon shot noise from the reference arm **622a** is above the detector circuit noise. Ideally, one would select a non-polarizing beam splitter or a fiber coupler **618a** that couples as much light as possible to the sample arm **620a**, while leaving enough light from the reference arm **622a** to maintain the shot noise just above detector circuit noise.

Similar to the case of the sample arm **620a**, as the polarization direction is now rotated by 90° for the returned light wave from the reference arm **622a** to the polarizing beam splitter **614a**, except for the insertion loss, basically all of the returned light wave will now be channeled to port III of the polarizing beam splitter **614a**, assuming that the mirror **648a** in the reference arm **622a** preserves the light wave polarization state, if the non-polarizing beam splitter or the non-PM fiber coupler **618a** and the polarizing beam splitter **614a** are perfect, there will be no light returned to the light source **610a** and the polarization directions of the reference-arm-returned-light wave and the sample-arm-returned-light wave will be the same. If a short length of a non-PM fiber **650a** is used to guide the returned interfering light waves to a detector (or a light detection module) **652a** such that the polarization state is not altered by the short length of the non-PM fiber **650a**, the polarization state or direction of the returned light waves reaching the detector (or light detection module) **652a** will be fixed and predetermined. As has already been pointed out, this is especially beneficial to spectral domain optical coherence tomography (SD-OCT). It should also be mentioned that the use of the non-PM fiber **650a** is not absolutely necessary,

in fact, the detector or light detection module **652a** may be directly placed or bonded next to the PBS **614a** and in such a case, the requirement to focus the returned interfered light beam into a single mode fiber may be eliminated as a photodetector generally has a relative large light sensitive area and this may save cost for the systems.

It should be noted that while in Fig.6A, a fiber optics version of the first embodiment of the present invention is illustrated; a bulk optics based free space version is obviously a natural extension of the invention. It should be pointed out that in certain cases, the bulk optics version may provide other advantages. For example, with bulk optics, the two 45° Faraday rotators may be replaced by two quarter wave plates which may be less expensive, and the need to expand and collimate a light beam from a single mode fiber, and to refocus the expanded beam back into another single mode optical fiber, may be eliminated, which may also save cost for the system.

Fig. 6B shows a bulk optics version of the first embodiment of the present invention. As the bulk optics version is very similar to the fiber optics version, the description below will only mainly highlight the differences rather than repeating the details. The light source **610b** can be either a fiber pigtailed or non-fiber-pigtailed but collimated light source. If it is fiber pig-tailed, a collimating lens needs to be used to collimate the output beam. As in the fiber optics version case, the light source can be either originally linearly polarized or externally linearly polarized by placing a linear polarizer (not shown) directly after an unpolarized source or by using the polarizing beam splitter **614b** to polarize it. The light source **610b** is directed through a free space **612b** to the input port (port I) of a polarizing/polarization beam splitter (PBS) cube **614b**. It is desirable that the input linearly polarized light wave is already in the correct polarization state or direction and hence the optical power is substantially transmitted to the output port (port II).

The light wave from port II of the polarizing beam splitter **614b** is directed through a free space **616b** to a non-polarizing beam splitter (NPBS) **618b** with a desired optical power split ratio of $\frac{\alpha}{1-\alpha}$, such that most of the light is coupled to the sample arm **620b** and a small portion of the input light is coupled to the reference arm **622b**.

The light wave in the sample arm travels through a free space optical path **624b** to an optical probe module **630b**, in which the light beam is scanned and focused

onto a sample **632b**. A polarization manipulator such as a quarter wave plate or a 45° Faraday rotator **634b** is placed in the probe module **630b** to enable the polarization rotation of the returned light wave by 90°. Note that when a quarter wave plate is used, although it may be cheaper than a 45° Faraday rotator, the projected light wave onto the sample will be circularly polarized instead of linearly polarized as in the case of a 45° Faraday rotator. Hence the use of a quarter wave plate will not deliver a linearly polarized light wave to the sample **632b** as in the case of a 45° Faraday rotator, where a free space based polarization controller may be inserted in the sample arm path **624b** to deliver a desired polarization direction to the sample **632b** as in the fiber optics version case.

The returned light wave from the sample **632b** is collected by the probe module **630b**, directed back to the NPBS **618b**, where it is further split with a larger optical power splitting percentage of α back towards the PBS **614b**.

Similarly, for the reference arm, the use of a quarter wave plate or a 45° Faraday rotator **646b** will rotate the polarization direction of the returned light wave by 90°. Note that since the mirror **648b** does not need a preferred polarization state and there is generally no birefringence change for a light wave traveling in free space, a quarter wave plate can always be used anywhere in the reference arm, although a more expensive 45° Faraday rotator can also be used. In addition to an approximate optical path length matching between the sample arm and the reference arm, a dispersion matching optical element can also be used in the reference arm. Similar to the fiber optics version case, the optical delay line **642b** is preferably incorporated in the reference arm **622b**.

The light wave returned from the reference mirror **648b** is directed back through the same free space optical path **640b** to the non-polarizing beam splitter NPBS **618b** and is split with a smaller optical power percentage of $(1-\alpha)$ towards the polarizing beam splitter PBS **614b**.

Note that since the polarization direction of the returned light waves from both the sample arm and the reference arm have been rotated by 90° with respect to the original forward traveling light wave, basically all of the two returned light waves will now be channeled to port III of the polarizing beam splitter **614b**. Obviously, the polarization state or direction of the returned light waves reaching the detector (or light detection

module) **652b** will be fixed and predetermined. A detector or a detection module **652b** can be used to collect the two interfering light waves to convert the interfered optical power into an electrical signal for further processing.

Note that the optical path **650b** can be a free space path and can be shortened to a minimum by placing the detector or detection module **652b** next to the PBS **614b**. Alternatively, a fiber pig-tailed detector or detection module may be used and in such a case the optical path **650b** may represent a short length of optic fiber and wherein there will be a need to focus the free space light beam into such an optical fiber.

As a further extension to Fig.6A and Fig.6B, Fig.6C shows another free space optics version of an implementation of embodiment 1. Instead of using two polarization manipulators as in Fig.6A and Fig.6B, Fig.6C uses only one polarization manipulator **670c** in the common optical path portion between the PBS **614c** and the NPBS **618c** to rotate the polarization of the two returned light waves from the sample arm and the reference arm respectively to an orthogonal direction. Similar to the argument of Fig.6B, as the retuned light waves to the PBS **614c** have an orthogonal polarization, they will be completely channeled to port III and hence to the detector **652c** with a fixed or predetermined polarization direction.

It should be noted that the polarization manipulator **670c** can be either a quarter wave plate or a 45° Faraday rotator. A quarter wave plate is preferred here due to its lower price and in such a case, the light wave to the right side of the quarter wave plate will be circularly polarized and will be further split by the NPBS **618c** into the sample arm and the reference arm with a desired optical power split ratio. On the other hand, if a 45° Faraday rotator is used, the light wave to the right side of the Faraday rotator will be linearly polarized but with an azimuth orientation that is 45° with respect to the incident light wave on the left side of the 45° Faraday rotator. Such a linearly polarized light wave will be further split into the sample arm and the reference arm by the NPBS **618c** with a desired optical power split ratio. Note that in the latter case, a free space based polarization controller may be inserted in the sample arm path **624c** to deliver a desired polarization direction to the sample **632c** as in the fiber optics version case.

Upon reflection from the biological sample and the reference mirror, the returned light waves will be further split by the NPBS **618c** toward the polarization

manipulator **670c**. Due to the fact that the light wave propagating toward the PBS **614c** from the sample arm will have transmitted through the NPBS **618c** twice, whereas the light wave propagating toward the PBS **614c** from the reference arm will have been reflected twice by NPBS **618c**, the optical power delivery efficiency can hence be made very high by splitting most of the optical power to the sample arm.

It should be understood that the rest of the embodiment of Fig.6C is similar to what has been discussed for Fig.6A and Fig.6B and hence will not be repeated here. Note that the embodiment of Fig. 6C may be especially advantageous for free space based SD-OCT system such as SD-OCT microscopes as the cost is even lower than that of Fig.6B. It should also be understood that a combination of various features of Fig.6A, Fig.6B and Fig.6C can be selected to suit various applications. For example, one may select a fiber based sample arm for easy and flexible light delivery to a biological sample together with a 45° Faraday rotator to render the sample arm insensitive to birefringence fluctuations and, to save costs, the reference arm can be a free-space optics based configuration with a quarter wave plate.

EMBODIMENT 2

Fig. 7A is a diagram of the OCDR system according to a second embodiment of the present invention. The light source **710a** introduces to the system **700a** a linear polarized light wave either through a linearly polarized light source **710a** or by placing a linear polarizer (not shown) directly after an unpolarized source. The light source **710a** has a center wavelength within the optical spectrum range from ultra-violet to near infrared. It is preferably derived from a superluminescent diode (SLD), a light emitting diode (LED), a frequency swept laser, a short pulsed laser such as a Ti:sapphire laser, a photonic crystal fiber laser or a spontaneous emission based rare earth doped optical fiber broad band light source. The light source **710a** is coupled through a short length of a non-PM fiber **712a** to the input port (port I) of a polarizing/polarization beam splitter (PBS) **714a**. Assuming that the PBS has two polarization modes or directions that are in the vertical and horizontal directions respectively, compared to embodiment 1, the polarization direction of the input light wave of embodiment 2 is neither in the vertical nor in the horizontal direction but is rather selected to lie in a direction in between these two axis. As a result of this selection, assuming that there

is no loss of optical power at the PBS, a certain percentage of the input optical power (for example $\alpha_1 = 90\%$) will be channeled port II of the PBS **714a** and hence to the sample arm **720a** and the remaining input optical power (for example $(1-\alpha_1) = 10\%$) will then be channeled to port III of the PBS **714a** and hence to reference arm **722a**. It is well known to those skilled in the art that the polarization directions of the two light waves in the sample and reference arms are orthogonal or perpendicular with respect to each other. Note that the PBS **714a** may be based on a polarization beam splitter cube, in which case the light wave from a fiber needs to be collimated using, for example, a graded refractive index (GRIN) lens and refocused into another fiber using, for example, another GRIN lens, if this is desired. The PBS **714a** may also be purely fiber optics based in which case polarization-maintaining (PM) fibers may be present. It should also be noted that as the light source **710a** can be polarized or unpolarized, if it is polarized, a polarization-maintaining (PM) fiber may have already been pig-tailed for the light source and such a PM fiber can be used to connect the light source **710a** to the PBS **714a** to maintain the polarization state. It should be pointed out that non-PM fiber or PM fiber pig-tailed polarization beam splitters are commercially available and their price is much less than that of a fiber pig-tailed optical circulator. Hence such fiber pigtailed PBS may be used directly. Preferably, the polarized light wave from the light source arm is already in the desired polarization state or direction to enable a desired percentage of the input optical power to the sample and reference arms respectively. Note that compared to embodiment 1 of Fig.6A, the PBS **714a** of Fig.7A also serves the purpose of the fiber coupler **618a** of Fig.6A, i.e. to split the input optical power at a desired ratio into the sample and reference arms. If the input polarization state is not in the desired direction, a non-PM single mode fiber based polarization controller **711a** can be placed in front of the PBS **714a** to adjust the input polarization state to the desired direction. Although a non-PM fiber based polarization controller **711a** is preferred here, other types of polarization controller can also be used, for example, a bulk optical wave plate based polarization controller is also a choice. Meanwhile, in spite of the fact that a non-PM fiber pig-tailed polarizing beam splitter (PBS) is preferred here, this statement does not exclude the use of PM fiber pig-tailed PBS, although the latter may be more expensive than the former due to the additional requirement of rotational alignment of the PM fibers.

The polarized output from port II of the polarizing beam splitter **714a** is sent through a non-PM single mode fiber **724a** and an optical probe module **730a** to a sample **732a**. The non-PM single mode fiber **724a** can have any reasonable length as long as it approximately matches the length and dispersion property of the non-PM single mode fiber **740a** in the reference arm **722a**. It should be noted that here dispersion matching is desirable but not absolutely required. A preferred practice is to cut a single piece of a non-PM fiber into two pieces of substantially the same length with one for the sample arm and the other for the reference arm so that their dispersion property is also well matched.

The optical probe module **730a** includes some light beam shaping and focusing elements, light beam bending or steering or scanning elements (not shown) such as pivoted scanning or dithering mirrors, and a polarization manipulator such as a 45° Faraday rotator or a quarter wave plate **734a**. It should be noted that in the optical probe module **730a**, the arrangement of various optical elements can be of any order or sequence. Although it is preferred that a Faraday rotator **734a** is placed at the end of the sample arm just in front of the sample, in practice, it may be more reasonable to place the Faraday rotator **734a** before any translational or mechanically movable components, and perhaps the easiest place to put it is at the end or tip of the fiber **724a** as such a Faraday rotator tipped fiber piece is commercially available.

Light reflected from various optical interfaces or scattered from within the sample **732a** is collected by the same optical probe module **730a** and is directed back through the same non-PM optical fiber **724a** in the sample arm **720a** to the PBS **714a**. Note that due to the use of the 45° Faraday rotator **734a** as discussed previously with reference to Fig. 4, the polarization state or direction of the returned light wave will be rotated by 90° after double-passing the non-reciprocal Faraday rotator **734a** to an orthogonal direction with respect to the polarization direction of the original forward-propagating light wave before it hits the Faraday rotator **734a**. Thus, except for the sample or components in the sample arm after the Faraday rotator **734a**, any birefringence-induced polarization sensitivity or fading effect introduced to the sample arm light wave in the forward direction will be completely compensated for or cancelled when the light wave propagates in the backward direction. It should be highlighted that because of this feature, if a polarization controller is included in the fiber section **724a** of the sample arm **720a**, a desired final polarization state of the light

beam shining onto the sample can be selected to take full advantage of a biological sample if its light reflection or scattering property is polarization dependent and this polarization controlling will obviously not influence the final polarization direction of the returned light wave from the sample arm. For example, one can maximize the final optical interference signal if, for certain optical boundaries or interfaces, the amount of reflected light is more intense in one polarization direction than the other or to examine the birefringence properties of a biological sample using this approach.

On the other hand, if the sample is a biological sample that has a relatively large birefringence that can not be ignored and is more or less predictable, the polarization manipulator may be selected in such a way that when it is combined with the birefringence of the biological sample, a substantially 90° polarization direction rotation for the returned light wave with respect to the original forward propagating light wave is realized. Such a polarization manipulator can be either a single wave plate or a combination of a polarization controller and a wave plate, wherein the polarization controller can select a desired polarization direction with respect to the wave plate and the biological sample, and the wave plate can combine its birefringence with that of the biological sample to provide a net quarter wave plate effect.

When the returned light wave from the sample arm **720a** returns to the PBS **714a**, as the polarization direction is now rotated by 90°, except for the insertion loss which can be assumed to be zero for ease of discussion, basically all of the returned light wave will now be channeled to port IV of the polarizing beam splitter **714a** (as is well known to those skilled in the art), and if the polarizing beam splitter **714a** is perfect, there will be no light returning to the light source **710a**. This is obviously an advantage as has already been discussed with reference to Fig.2, because any returned light to the light source might disturb the light emitting property.

For the light wave sent through port III of the PBS **714a** to the reference arm **722a**, the wave will propagate to a polarization manipulator such as a Faraday rotator or a quarter wave plate **746a** and a mirror **748a** through a non-PM single mode fiber **740a** that is approximately matched in length and dispersion property with the non-PM single mode fiber **724a** in the sample arm **720a**. It is preferred that the optical delay line **742a** for depth scanning is incorporated in the reference arm **722a**. This reference delay line **742a** may be a

transmissive one to be implemented in the fiber section **722a**, which can be achieved by wrapping a certain length of optical fiber around a piezoelectric stretcher. In fact, for a standard polarization sensitive OCT configuration such as those shown in Fig.1 and Fig.2, such an optical fiber wrapped PZT based optical delay line will generally introduce a substantial amount of polarization fading as a result of the birefringence change during the optical path length scanning or optical phase modulation process, but with the presently invented configuration, this is no longer an issue because of the polarization insensitivity nature and hence it might be advantageous to use such a fiber wrapped PZT based optical path length delay line. Although implementing the optical delay line in the reference arm **722a** is preferred here, it should be noted that the optical delay line can also be located in the sample arm or both arms may have an optical delay line with the two operating in a push-and-pull mode or in any other manners as desired such as with one modulating the path length to achieve a depth scan and the other modulating the optical phase to obtain a high carrier frequency for the interference signal. Alternatively, an independent optical delay line may be used after the fiber **740a** and a good example is a grating based phase control optical delay line as disclosed in U.S. Patent Nos. 6,111,645 and 6,282,011. Other retro-reflective optical delay lines such as those employing corner mirror(s) or corner prism cube(s) may also be used. The overall optical path length for the reference arm **722a** should roughly match that of the sample arm **720a** and this can be achieved by letting the reference light wave traveling through some free space and/or some other optical elements. By roughly matching the overall optical path length between the reference arm **722a** and the sample arm **720a**, the requirement for the scan range of the optical delay line **742a** can be lowered and data acquisition time for one depth scan can thus be reduced to a minimum. The reference arm **722a** may also contain some light beam shaping and/or focusing optical elements **744a** in addition to the polarization manipulator such as a 45° Faraday rotator **746a** and the mirror **748a**. The position of the 45° Faraday rotator **746a** is preferably at the end of the reference arm **722a** and right in front of the mirror **748a** so that polarization fading caused by any birefringence or birefringence fluctuations introduced by all the optical elements prior to the Faraday rotator **746a** in the reference arm **722a** can be completely compensated for and hence cancelled. However, it should be noted that the 45°Faraday rotator **746a** can be placed anywhere between the end of the non-PM fiber **740a** and the mirror **748a**. It is perhaps even

more economic to directly use a mirrored 45° Faraday rotator with a non-PM fiber pig-tail as such a device is now commercially available, and in such a case, the reference arm fiber **740a** may be selected to be longer than the sample arm fiber **724a** such that the overall optical path length between the sample arm **720a** and the reference arm **722a** is roughly matched.

Similar to what has been discussed for the sample arm **720a**, the light wave returned from the mirror **748a** is collected by the same optical element(s) **744a** & **746a** and is directed back through the same non-PM optical fiber **740a** in the reference arm **722a** to the PBS **714a**. Due to the use of the polarization manipulator such as a 45° Faraday rotator **746a**, the polarization state or direction of the returned light wave will be rotated by 90° after double-passing the non-reciprocal Faraday rotator **746a** to an orthogonal direction with respect to the polarization direction of the original forward-propagating light wave in the reference arm **722a** before it hits the Faraday rotator **746a**. As a result, any birefringence-induced polarization sensitivity or fading effect introduced to the reference arm light wave in the forward direction will be completely compensated for or cancelled when the light wave propagates in the backward direction.

When the returned light wave from the reference arm **722a** arrives at the PBS **714a**, its polarization direction is now rotated by 90°, except for the insertion loss which is assumed zero for the ease of discussion, basically all of the returned light wave will now be channeled to port IV of the polarizing beam splitter **714a**, assuming that the mirror **748a** in the reference arm **722a** preserves the light wave polarization state, if the polarizing beam splitter **714a** is perfect, there will be no light returned to the light source **710a.** Compared to embodiment 1, a major difference here is that the polarization directions of the reference-arm-returned-light wave and the sample-arm-returned-light wave are orthogonal or perpendicular to each other. As a result, if one directly puts a detector to detect these two waves, there will be no interference signals as is well known to those skilled in the art.

To extract the interference signal, one needs to project the two orthogonally polarized light waves onto a common polarization-passing-through-direction and there are two possible approaches. The first one is to arrange another polarizing/polarization beam splitter **752a** in such a way that its azimuth orientation is substantially at 45° with respect to that of the first polarizing beam splitter **714a**. As is well known to those skilled in the art, by

doing so, a balanced heterodyne detection scheme can be realized as shown in Fig. 7A. To save cost, the second polarizing beam splitter **752a** can actually be glued or bonded to the first polarizing beam splitter **714a** so that they become a rigid solid module together with the two detectors D1 and D2.

However, the above statements should not exclude the use of a short length of a non-PM fiber **750a** between the first PBS **714a** and the second PBS **752a**, as long as the polarization state is not altered by the short length of the non-PM fiber **750a**. The statements also should not exclude the use of a PM fiber between the first PBS **714a** and the second PBS **752a**, and the reason for this is that a PM fiber pig-tailed PBS with four ports are commercially available and hence can be readily used.

The second approach to extract the interference signal from two orthogonally polarized optical light waves is to use a simple analyzer together with only one detector. As an example, the second polarizing beam splitter can be azimuthally oriented in such a way that an enhanced interference fringe visibility is achieved together with shot noise limited detection as has been discussed before. For example, the orientation direction of the second PBS **752a** can be chosen such that while a smaller amount of the optical wave from the reference arm is projected to the polarization-passing-through-axis of the analyzer and a lager amount of the optical wave from the sample arm is projected to the same polarization-passing-through-axis of the analyzer, the amount of optical power from the reference wave also gives a photon shot noise from the reference arm that is just above the detector thermal noise. In fact, in term of optical power delivery efficiency, the second PBS **752a** now acts as an unbalanced beam combiner with a non-50/50 power split ratio, $\frac{\alpha_2}{1-\alpha_2}$, and the optical delivery efficiency is similar to that of Fig. 2Aii, but the present invention is Michelson interferometer based and it makes the system insensitive to polarization fading. It should be pointed out that there is no absolute need to use a cube based second polarizing beam splitter **752a** as an analyzer and in fact, it is much cheaper to use a thin film based analyzer that has only one polarization-passing-through-axis and it is even more economical to glue or bond such a thin film based analyzer **754a** to the first PBS **714a**, as long as the polarization-passing-through-axis is properly oriented (See insert to Fig. 7A). In fact, it might be even more economical to fix or bond a detector (e.g. D1) and the thin film analyzer **754a** to the

first PBS **714a** and in such a case, the requirement to focus the returned light waves into a single mode fiber can be eliminated as a photodetector generally has a relative large light sensitive area and this may save cost for the systems.

Note, however, that these statements should not exclude the possibility of having a PM or non-PM fiber in between the first PBS **714a** and the second analyzer. Also they should not exclude the form of the analyzer which can be either a PBS or a film based analyzer or even a fiber version of an analyzer such as a piece of a polarizing fiber.

With the use of the analyzer, the polarization state or direction of the returned light waves reaching the detector (or light detection module) D1 will be fixed and predetermined. As has already been pointed out, this is especially beneficial to spectral domain optical coherence tomography (SD-OCT), also referred to in the literature as frequency or Fourier domain optical coherence tomography, since in such a system, the grating used to disperse the constituent wavelength components of the broadband optical signal is generally sensitive to the polarization direction of the input beam and hence a fixed or predetermined polarization direction of the input beam to the grating will be extremely beneficial.

It should be noted that while in Fig.7A, a fiber optics version of the second embodiment of the present invention is illustrated, a corresponding bulk optics based free space version could also be implemented. As pointed out already, in certain cases, the bulk optics version may provide other advantages. For example, with bulk optics, the two 45° Faraday rotators, may be replaced by two quarter wave plates, and the need to expand and collimate a light beam from a single mode fiber, and to refocus the expanded/collimated beam back into another single mode optical fiber, may be eliminated, which may save cost for the system.

Fig. 7B shows a bulk optics version of the second embodiment of the present invention. In order not to repeat all the details again, the description below will only highlight the main differences. The light source **710b** is preferably a non-fiber-pigtailed, collimated light source such as one with a TO can package, but can be fiber pig-tailed, in which case a collimating lens needs to be used to collimate the output beam. As in the fiber optics version case, the light source can be either originally linearly polarized or externally linearly polarized by placing a linear polarizer **713b** directly after an unpolarized source.

The light source **710b** is directed through a free space **712b** to the input port (port I) of a polarizing/polarization beam splitter (PBS) cube **714b**. It is assumed that the input linearly polarized light wave is already in a desired polarization state or direction such that a large portion of input optical power is split into the sample arm **720b** via port II of the PBS cube **714b** and a small portion of the input optical power is split into the reference arm **722b** via port III of the PBS cube **714b**.

The light wave in the sample arm travels through a free space optical path **724b** to an optical probe module **730b**, in which the light beam is scanned and focused onto a sample **732b**. A quarter wave plate or a 45° Faraday rotator **734b** is placed in the probe module **730b** to enable the polarization rotation of the returned light wave by 90°. Note that when a quarter wave plate is used, although it may be cheaper than a 45° Faraday rotator, the projected light wave onto the sample **732b** will be circularly polarized instead of linearly polarized as in the case of a 45° Faraday rotator. Hence the use of a quarter wave plate will not deliver a linearly polarized light wave to the sample **732b** as in the case of a 45° Faraday rotator where a free space based polarization controller may be inserted in the sample arm path **720b** to deliver a desired polarization direction to the sample **732b** as in the fiber optics version case.

Assuming that when reflecting the incident light wave, the biological sample preserves the polarization state, then the returned light wave from the sample **732b**, after being collected by the probe module **730b**, and directed back to the PBS **714b**, will have its polarization direction rotated by 90° with respect to the original forward propagating beam. As is well known to those skilled in the art, the returned sample wave will now be totally directed to port IV of the PBS **714b**.

Similarly, for the reference arm, the use of a quarter wave plate or a 45° Faraday rotator **746b** will rotate the polarization direction of the returned reference light wave by 90°. Since the mirror **748b** does not need a preferred polarization state and there is generally no birefringence change for a light wave traveling in free space, a quarter wave plate can always be used anywhere in the reference arm **722b**. In addition to an approximate optical path length matching between the sample arm and the reference arm, a dispersion matching optical element can also be used in the reference arm **722b**. Similar to the fiber

optics version case, the optical delay line **742b** is preferably incorporated in the reference arm **722b**.

The light wave returned from the reference mirror **748b** is directed back through the same free space optical path **740b** to the polarizing beam splitter PBS **714b**. Now that its polarization direction has been rotated by 90° with respect to the original forward propagating beam, as is well known to those skilled in the art, the returned reference wave will now be totally directed to port IV of the PBS **714b**.

As in the fiber optics version case, the two waves exiting port IV of the PBS **714b** have orthogonal polarization and in order to extract the interference signal, an analyzer or another PBS needs to be used. While balanced heterodyne detection can be realized using a 45° azimuthally oriented PBS **752b** together with two detectors, a less expensive approach is to use a thin film based analyzer **754b** with one detector (See insert, Fig. 7B). Obviously, the polarization state or direction of the interfering light waves reaching the detector(s) will be in the polarization-passing-through-direction of the analyzer and hence is fixed and predetermined by the analyzer **754b** or the second PBS **752b**, which as mentioned before, is beneficial to SD-OCT detection scheme.

Note that the optical path **750b** can be a free space path and can be shortened to a minimum by placing the analyzer **754b** or the second PBS **752b** together with the detector(s) next to the PBS **714b**. Alternatively, a fiber pig-tailed detector or detection module may also be used and in such a case there will be a need to focus the free space light beam into such an optical fiber.

As has been discussed for embodiment 1, it should be understood that a combination of various features of Fig.7A, and Fig.7B can be selected to suit various applications. For example, one may select a fiber based sample arm for easy and flexible light delivery to a biological sample together with a 45° Faraday rotator to render the sample arm insensitive to birefringence fluctuations and, to save costs, the reference arm can be a free-space optics based configuration with a quarter wave plate.

It should be pointed out that for the two embodiments, although 45° Faraday rotators and quarter wave plates have been mentioned, the embodiments should not exclude the possibility of using other optical elements to achieve the same goal of rotating the polarization direction of the returned wave to an orthogonal direction with respect to the

original forward propagating light wave. As is well known to those skilled in the art, there are other thickness for a Faraday rotator and a wave plate that can serve the same purpose and examples include Faraday rotators with rotation angles equal to 45° + M×90°, or wave plate having an overall retardation of $\frac{\lambda}{4}+M\frac{\lambda}{2}$, where M is an integer and λ is the central wavelength of the light source. Hence it should be understood that the 45° Faraday rotator or quarter wave plate can be replaced accordingly as long as the final polarization direction of the returned light wave is in the orthogonal direction with respect to the original forward propagating light wave. Furthermore, even if the birefringence property of the light path in either the sample arm or the reference arm may change or fluctuate, as long as such a change can be monitored and compensated dynamically, one could also achieve the same goal of rotating the returned light wave polarization to the orthogonal direction and a good example is a dynamically controllable quarter-wave plate (QWP), such a QWP can be dynamically tuned in response to changes or fluctuations in the either the sample arm or the reference arm to ensure a total returned polarization direction rotation by 90°.

It should be highlighted that the configurations of the present invention (both embodiment 1 and 2) are relatively simple and hence of relatively low cost. Compared with a standard traditional Michelson interferometer based OCDR system, the main difference in terms of optical components used include a polarizing beam splitter and one or two polarization manupulator(s). Considering that a polarization insensitive fiber pig-tailed optical circulator contains a number of more optical elements in addition to the use of a polarizing beam splitter and some Faraday rotators, the configurations of the present invention will hence cost less than a configuration that include a polarization insensitive fiber pig-tailed optical circulator. By reviewing the prior art configurations, it can be seen that for many of these configurations, their cost will be even higher due to the use of polarization maintaining fibers, the use of additional 22.5° Faraday rotators and other additional optical components. Also note that the present configuration of the invention is compact and is very similar to a standard conventional non-PM fiber based Michelson interferometer configuration, which can be easily modified to the present invention configuration.

It should also be understood that the present invention is particularly beneficial for application in spectral domain OCT (SD-OCT), as in such a case it is preferred

that the polarization state of the interfering light waves sent to the detection module be fixed or predetermined as the module contains a polarization dependent optical element such as a grating. Fig. 8 shows an example of such a SD-OCT detection module. Assuming that the interfered light wave is guided in an optical fiber **810**, a lens **820** can be used to collimate the beam and project it onto a blazed reflection grating **830**. It is preferable that the optical fiber be short to minimize polarization effects in the fiber. The grating **830** will disperse the various wavelength components of the light source into parallel beams of different diffraction angles. It should be noted that while a blazed reflection grating has been shown here, other optical dispersing elements can be used to achieve the same goal. Some examples include a transmission grating, an arrayed waveguide grating, and a prism. Lens **840** can be used to focus the various beams of different diffraction angles and hence different wavelength components onto a detector array **850**. Due to the fact that a fixed optical path length difference between a reference reflector and a sample reflection site will correspond to different optical phase delays for different wavelength components, the various wavelength components will hence give rise to alternating constructive and destructive interference fringe on the detector array **850**. As a certain reflection site in the sample will lead to a certain spatial frequency of the interference fringe on the detector array, different reflection sites from the sample will hence result in interference fringes of different spatial frequencies. Consequently, a Fourier transform of the interference fringes of different spatial frequencies will provide information simultaneously on the various reflection sites of the sample. In such a case, the optical delay line does not need to be scanned.

Alternatively, the optical delay line may be used to achieve a phase shift modulation in order to determine the relative phase of the light returning from the reference and sample arm. One example of this is disclosed by Vakhtin et al. (Vakhtin, Andrei B. et al. (2003) "Differential spectral interferometry: an imaging technique for biomedical applications", Optics Letters, Volume 28, Issue 15, 1332-1334). Another example is given by Fercher (US Patent No. 6,377,349)

The foregoing description of the invention is presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described to best explain the principles

of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated.

REFERENCES OF INTEREST

The following references are incorporated herein by reference.

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